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GLOBAL ELECTRICAL CURRENTS

By

Willis L. Webb

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ATMOSPHERIC SCIENCES LABORATORY
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ABSTRACT

The atmospheric electrical structure of the earth is postulated to be controlled by a motivating force in the lower ionosphere which is produced by interaction between neutral atmosphere tidal circulations and the ionospheric plasma in the presence of the earth's magnetic field. Associated electric fields power the dynamo currents through the Hall effect with a resulting development of a gross electric potential distribution in the lower ionosphere. Asymmetries in these hemispheric potential distributions result in exospheric current flows in low L-shells, and larger differences in potential produced [illegible] dynamo return current flows in high magnetic latitudes result in strong currents through high L-shells between auroral zones. Vertical thunderstorm currents with their associated lightning discharges effectively connect the earth to a low potential region of the dynamo circuit and thus supply the earth with an average negative charge which motivates a leakage tropospheric electrical circuit. In addition, the dynamo currents maintain the magnetic polar regions at different potentials with a resulting electrical exchange with the solar wind through the earth's near space. These considerations indicate that observed electrical and variable magnetic phenomena near the earth are all part of a single comprehensive electrical current system.

CONTENTS

1. Introduction

A comprehensive concept of the earth's electrical structure has been derived (Webb, 1968b) which provides a framework into which known electrical phenomena may be fitted. A principal item in this new concept is the nature of the motivating force which powers this global electrical system. This power source is hypothesized to result from interaction between the neutral and ionized components of the lower ionosphere, a process which derives its energy from the stratopause thermal tidal circulations. Many details of this concept have not been investigated, in part because of the deep divisions which have developed between various segments of the geo-sciences which are integrated by the concept. It is attempted here to delineate the overall picture in a form which will facilitate comprehensive consideration of the concept.

In addition, further analysis of the basic physical processes which produce the general motivating force is presented. These considerations support the concept of a unified global structure, as opposed to the past theories which have separated the earth's electrical structure into more or less independent telluric (Chapman and Bartels, 1962), tropospheric (Chalmers, 1967), lower ionosphere dynamos (Chapman and Bartels, 1962), auroral and airglow (Chamberlain, 1961) and exospheric currents (Hines, et al., 1965). The several physical processes which have been postulated in attempts to understand these phenomena separately are not questioned at this point. It is presumed, however, that these processes are secondary to the global structure, even though specific processes may exert a firm local control.

2. Global Circuitry

The global electrical circuitry model postulated here is illustrated in Fig. 1. The time selected for this presentation is at noon during the summer solstice of the Northern Hemisphere, when, for geometric and other reasons, conjugate points will generally exhibit higher electric potentials in the Northern Hemispheric dynamo regions. The nomenclature employed in Fig. 1 is:

R - resistance
I - current
t - telluric circuits
n - Northern Hemisphere
s - Southern Hemisphere
f - fair-weather vertical circuits
c - convective vertical circuits
h - high latitudes
ℓ - midlatitudes
d - zonal dynamo circuits
e - equatorial
i - inner radiation belt circuit

2 - outer radiation belt circuit
3 - solar wind circuit

The basic driving force is oriented west-east near the 100 km level in low latitudes of each hemisphere during local daytime. This force drives the dynamo currents (I_d) of more than 10^5 amperes which produce a complex electric potential distribution in the lower ionosphere with hemispheric differences of the order of 10^6 volts. The earth, located approximately 100 km under the spherical shell which contains the dynamos, is connected to the dynamo circuits by vertical convective currents (I_c), principally in late afternoon and evening at low latitudes where the dynamo potentials are negative relative to noontime. This geometry impresses an observed negative charge of more

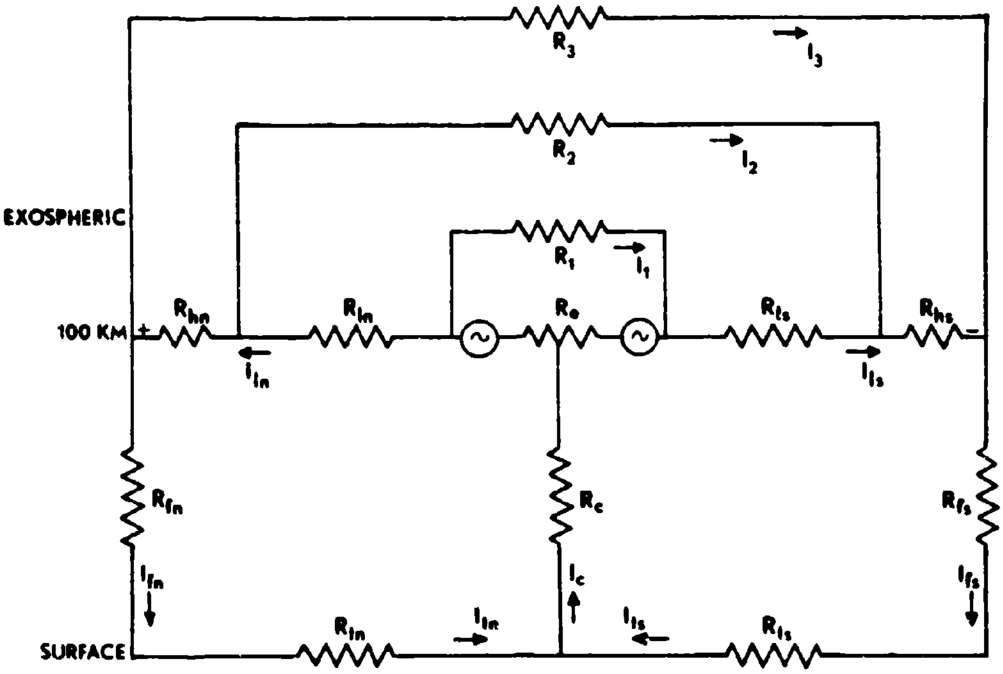

Figure 1. Schematic Diagram of the Global Electrical Circuitry for the Local Noon Meridian.

than 10^5 coulombs on the earth, which in turn produces an approximately symmetrical 10^3 amperes vertical current (I_f) through the fair-weather semiconducting lower atmosphere with associated telluric currents (I_t) through the earth's crust to thunderstorm regions.

In general, the electric potentials at conjugate points of the two hemispheres will not be equal. In low latitudes exospheric currents (I_1) will flow along magnetic field lines principally to relax potential differences imposed by differences in the basic dynamo driving forces. Auroral zone hemispheric potential differences will produce larger exospheric currents (I_2) at high magnetic latitudes, principally as a result of the asymmetry between the rotational and magnetic systems.

The final supplementary current path is formed by interaction of the earth's magnetosphere with the solar wind. Polar regions of the lower ionosphere will be maintained at different electrical potentials by the dynamo currents, and currents (I_3) through the solar wind plasma will result. It is probable that the geo-segment of this circuit will incorporate the I_2 circuit. During strong solar disturbances this current is known to become intense, approaching the 10^5 amperes of the dynamo circuits, although in general the exospheric currents are orders of magnitude smaller than the dynamo currents.

The earth's global electrical structure is than established by the potential field of the dynamo currents. Tropospheric and exospheric electrical structure is formed by leakage current paths which are controlled by the basic dynamo potentials.

3. The Dynamo Driving Force

The dynamo currents represent the principal geo-electric phenomenon, with average intensities which are two orders of magnitude greater than other circuits. An understanding of the earth's electrical structure requires that the force which drives these lower ionosphere currents be clearly delineated.

A new attempt at this problem has been made by Webb (1968a, 1968b, 1969) based on an assumed net vertical motion imposed on the upper atmosphere by tidal circulations of the stratopause regions. The characteristic cold mesopause indicates, in agreement with other observations, the presence of turbulent flow in the mesosphere to transport heat downward through adiabatic processes. A model of the general daytime vertical structure of molecular and eddy transport coefficients based on limited amounts of data (Lettau, 1951; Booker, 1956; Zimmerman and Champion, 1963; Kellogg, 1964; Johnson and Wilkins, 1965) is presented in Fig. 2. Higher values of eddy transport coefficients have been reported in the 80 to 150 km region (Zimmerman and Champion, 1963) but the molecular diffusion stratification which is observed above approximately 105 km (Blamont and de Jager, 1961) indicates that a portion of the observed values may result from electrically forced diffusion of the ionized trail sensors. These considerations then indicate

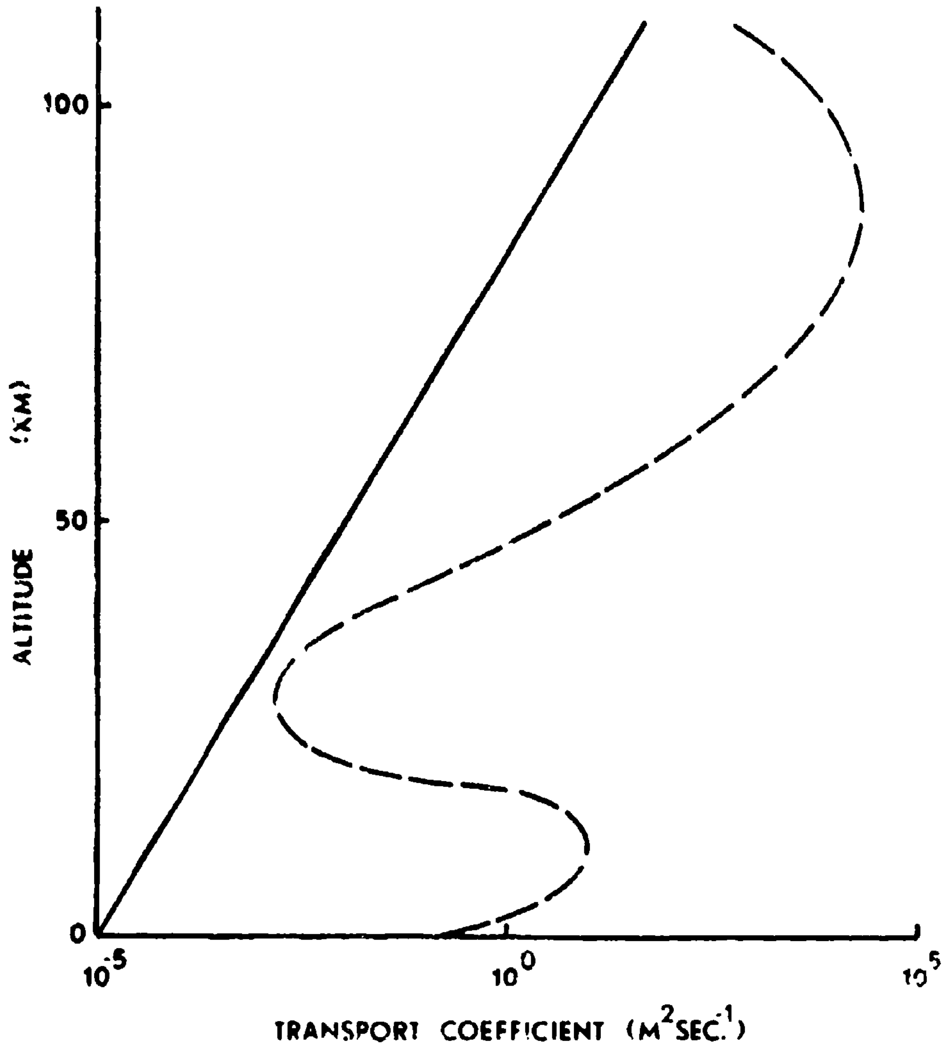

Figure 2. Model Molecular (solid curve) and Eddy (dashed curve) Diffusion Profiles

that the 70-100 km region is characterized by eddy transport coefficients in the range of $10^3 - 10^5$ m^2sec^{-1}.

Now the daytime electron-positive ion concentration (n) in the 70-100 km region varies over roughly three orders of magnitude, with a 100 km value of approximately 10^{11} electrons and positive ions per cubic meter. Negative charged particle lapse rates of 5×10^6 p m^{-4} at 100 km, 8×10^5 p m^{-4} at 90 km and 10^5 p m^{-4} at 80 km with this eddy transport (Fig. 2) will produce a downward flux of collision-controlled charged particles given by the relation

$$F = -D_e \frac{\partial n}{\partial h} . \quad (1)$$

As has been pointed out before (Fejer, 1965; Webb, 1968b), in this region of the atmosphere collision processes will transport positive ions but are ineffective in transporting electrons. Downward transport of positive ions by these eddies in an electrically neutral atmosphere will effect charge separation at a nominal velocity given by

$$v = \frac{F}{n} \quad (2)$$

The nominal downward velocities of positive ions under the above conditions will then be of the order of 1 mps at 80 km, .8 mps at 90 km and .5 mps at 100 km.

As was shown by Webb (1968b) such charge separation will, in equatorial regions, result in production of an upward-directed electric field which will force positive ions to migrate upstream with an equal speed so that electrical equilibrium is achieved. This latter situation is described by the relation

$$qE = M\nu w \quad (3)$$

where q is the particle charge, E is the equilibrating electric field, M is the particle mass, ν is the collision frequency and w is the particle velocity relative to the medium. The data presented above with the assumptions of Webb (1968b) indicate that electric fields directed upward with maximum intensity of 0.2 v m^{-1} at 80 km will be generated by this mechanism. At night this mechanism will be reduced in intensity by approximately two orders of magnitude as a result of a similar decrease in electron density. This situation has been shown (Webb, 1968a; 1968b) to be adequate to produce, through the Hall effect, an electric potential field which is consistent with known electrical phenomena of the region.

The above discussion and that of Webb (1968b) indicate that the driving forces of the dynamo currents are reasonably derived from vertical charge separation produced by collision processes in the circulations and turbulence produced by the stratopause thermal tides.

4. Tropospheric Electrical Structure

The fair-weather electrical structure of the lower atmosphere has been extensively explored (Chalmers, 1967). It is variable, with a general resistivity vertical structure of the type illustrated in Fig. 3 (Cole and Pierce, 1965). Here the bulk resistivity of the air exhibits its characteristic high value near the surface, decreasing rapidly with height so that the vertical path resistance is established by the resistance of the lower few kilometers. Almost 98% of the total vertical path resistance of roughly 1.8×10^{17} ohm m^2 is obtained in the first 10 km, and almost 90% is obtained in the first 5 km.

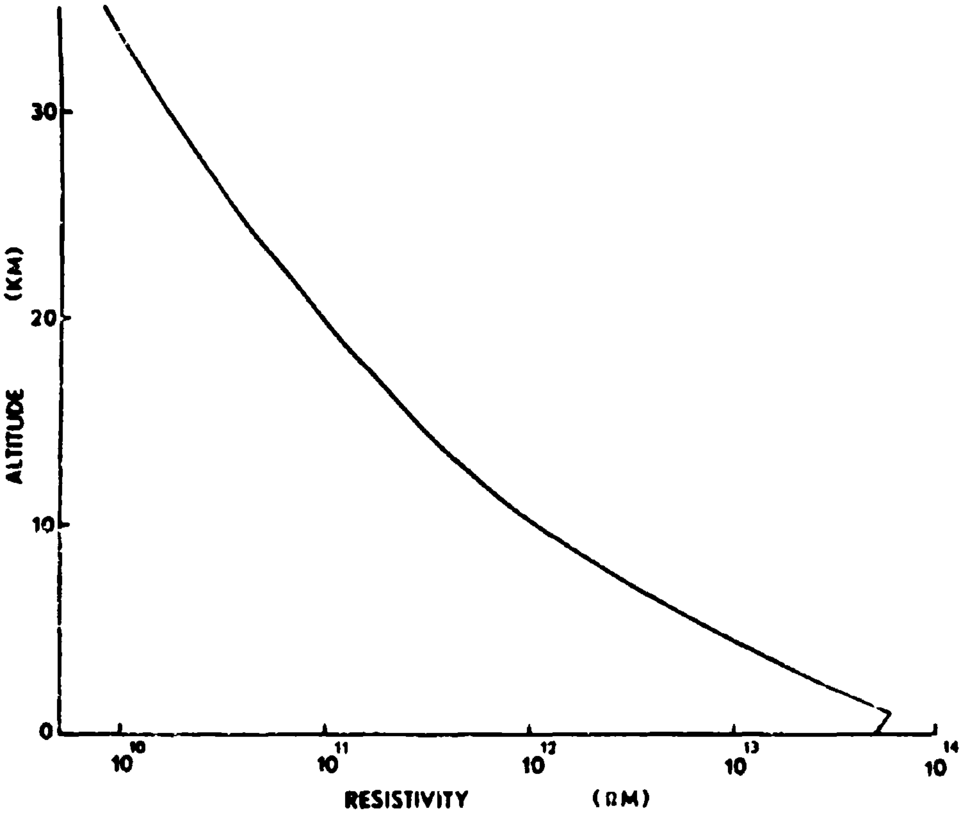

Figure 3. Typical Low-Latitude Vertical Resistivity Structure of the Troposphere and Lower Stratosphere.

In the stable fair-weather case, the vertical distribution of atmospheric space charge which produces the observed change in potential gradient can be calculated approximately from the relation

$$\rho = -\varepsilon_o \frac{\partial^2 V}{\partial h^2} , \qquad (4)$$

where V is the electric potential, and $\varepsilon_o = 8.854 \times 10^{-12}$ farads per meter is the permittivity of free space. Neglecting horizontal currents, the fair-weather electric current of the lower atmosphere will be constant with height, and, to a good approximation (Ohm's law), the potential distribution has the character of the resistivity curve of Fig. 3, with an overall potential difference of approximately 3×10^5 volts. By applying Eq.4 to these data, a representative vertical fair-weather space charge distribution is obtained as illustrated in Fig. 4. Clearly, the positive space charge of the atmosphere which must face the observed surface charge density of approximately -8.8×10^{-10} coulombs m^{-2} is principally contained in the lower troposphere. The traditional leaky capacitor concept of fair-weather electrical structure is thus modified to include a diffuse upper

plate located in the lower troposphere. The fair-weather troposphere capacitor plate contains a total positive space charge of approximately 400,000 couloml s, with a roughly equal negative charge on the surface of the earth. In addition, the vertically integrated space charge of the dynamo region (75 - 120 km) of roughly 10^{-14} coulombs m^{-2} is negligible compared to these tropospheric space charges.

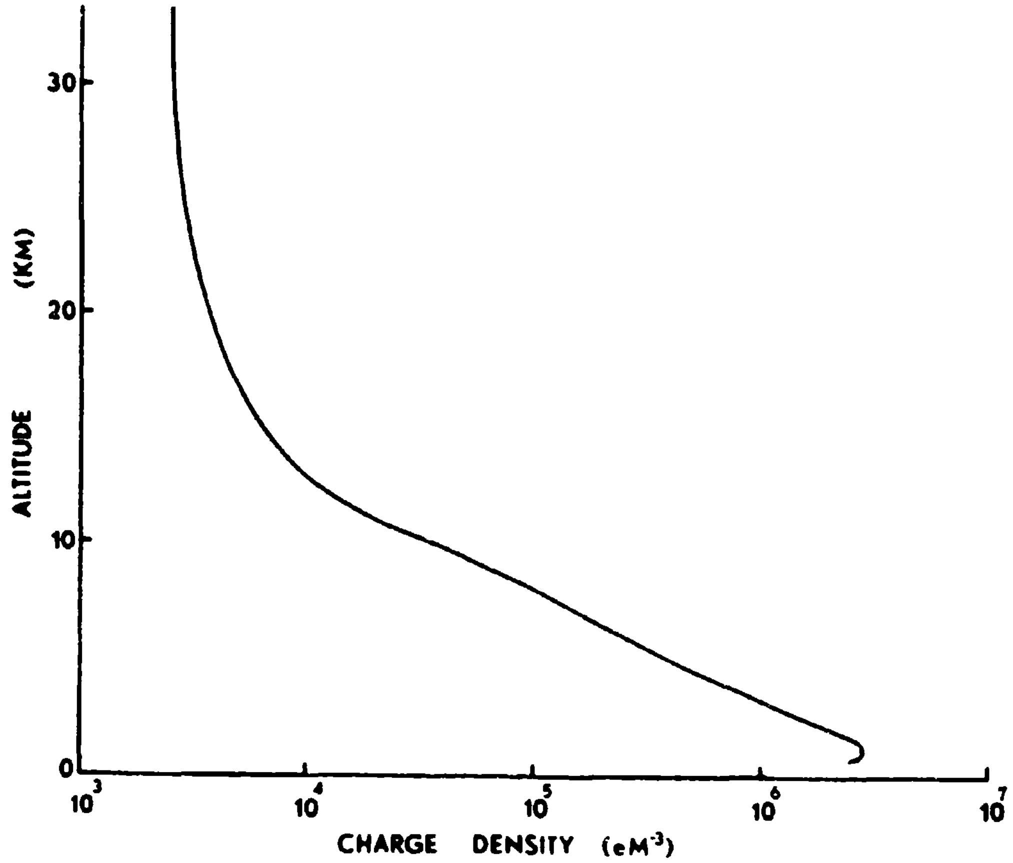

Figure 4. Typical Low-Latitude Vertical Structure of the Atmospheric Fair-Weather Positive Electric Space Charge.

The very low electrical mobility of most tropospheric ions in the boundary layer indicates that, in the presence of the general fair-weather potential gradient, electrically forced molecular diffusion will be, on occasion, exceeded in intensity by eddy diffusion. Mixing produced by thermal and frictional effects may dominate electrical physical processes under certain conditions so that the electrical structure which results frequently deviates from the simple picture of a homogeneous, stratified, static fair-weather field which is assumed above.

Certain features of the tropospheric electrical structure are comparatively static. This is true of any high impedance circuit, however, and does not alter the basically dynamic nature of earth electrification. The gross capacitance and charge of the earth's tropospheric electrical system ($C_e \sim 1$ farad) and small vertical current densities (approximately 2×10^{-12} amperes m^{-2}) of the troposphere effectively filter the variable aspects of atmospheric electricity, shielding the surface layers from the very dynamic aspects of higher levels.

The fair-weather capacitor electrical structure described above is effectively disrupted by occurrence of convective systems. Air that is rich in positive charge (Fig. 4) is assembled by the lateral flow, immobilized by droplets at low levels (1-2 km), and transported vertically by these convective systems in a thin column which spans the lower 10-25 km of the atmosphere as is illustrated in Fig. 5. The relatively low

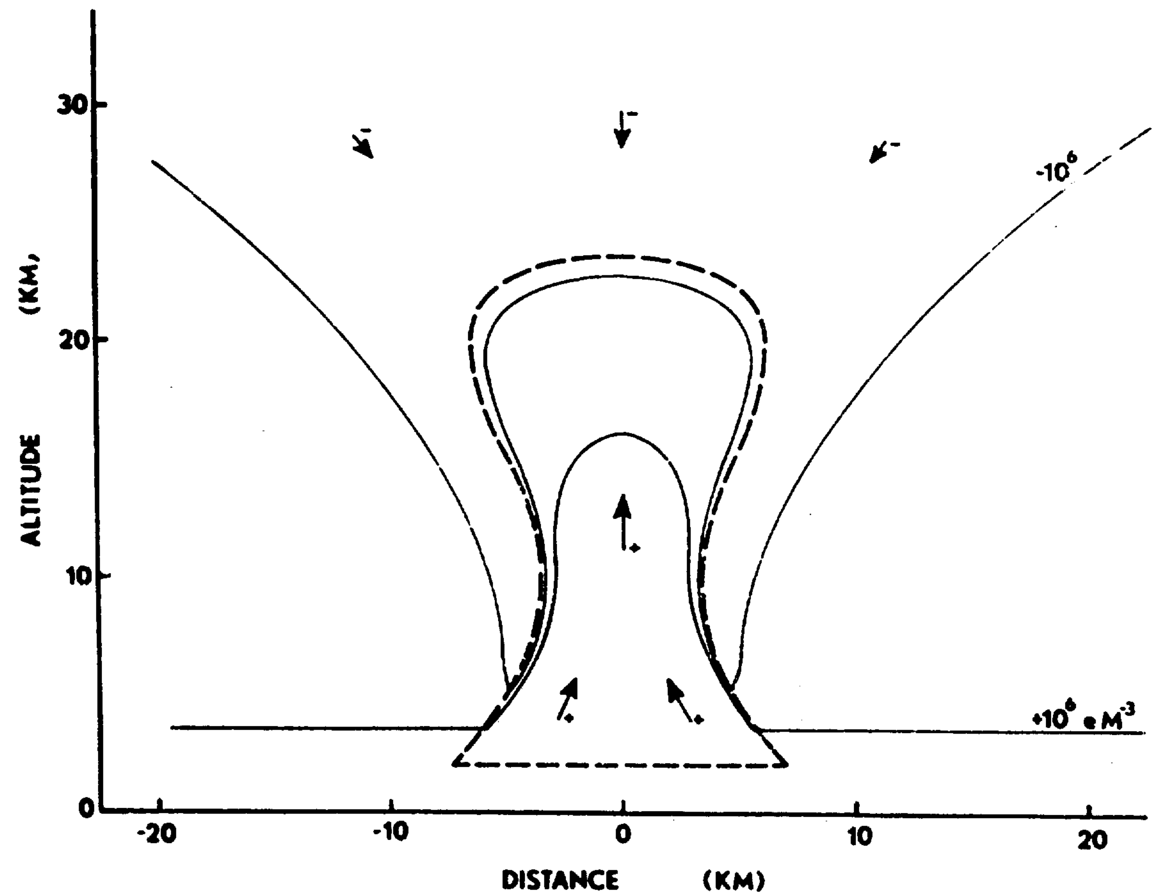

Figure 5. Initial space charge distribution associated with a convective cell before the dynamo potentials become involved. The dashed curve indicates the structure of the cloud, and the arrows indicate net motions of charged particles.

mobilities of tropospheric electrical charges are generally reduced drastically by condensation processes so that characteristic surface boundary layer electrical time constants of tens of minutes are effectively extended to beyond the half-hour lifetime of the average convective storm. If a 14 mps mean vertical flow through a 7 km diameter throat of a convective cloud (Goldman, 1968) with 10^6 excess positive charges per cubic meter (Fig. 4) is assumed, the more intense convective systems will transport approximately 10^{-4} coulombs of resident positive charge upward each second. A first response to this positive convective current will be an intensification of the fair-weather type field under the cell as the positive space charge converges. Rapidly, however, neutralization of this convection-borne positive space charge relative to the earth will be accomplished by negative ions in the upper atmosphere so that the negative surface charge on the ground under the cell will stabilize.

Introduction of this charge structure into the upper troposphere and lower stratosphere will result in strong response by the highly conducting upper atmosphere. Relaxation time constants ($T = \frac{\epsilon_o}{\sigma}$, σ - conductivity, Chalmers, 1967, p. 39) of approximately 100 seconds at 5 km, 20 seconds at 10 km, 4 seconds at 15 km and one second at 30 km in clear air around the thunderstorm may be expected. Upward transport of a cylindrical column of air containing roughly one coulomb of positive charge into the 5-15 km region of the storm can be expected to very quickly result in flow of an equal negative charge onto the edge of the cloud in the lower atmosphere. The mobility of the charge carriers in this conduction current will also decrease drastically when they enter the cloud as a result of capture by cloud droplets. This process will result in development of a thin sheath of negative charge around the positive core of the storm. The intruding positive space charge may then be eliminated by discharges within the cloud between these centers of charge concentration or by recombination at the top of the cloud where the cloud particles evaporate

The capacitance of this vertical cloud system per unit length can be estimated by the relation for specific capacitance of a cylindrical capacitor with inner plate at radius a and outer plate at radius b (Wilson, 1958)

$$c = \frac{2\pi\ \epsilon_o \epsilon}{\ln(\frac{b}{a})} \qquad \text{(farads per meter)} \qquad (5)$$

Using values of $\epsilon = 1$, a = 3.25 km and b = 3.5 km, the capacitance of this vertical cloud system is found to be approximately 7×10^{-10} farads m^{-1}. This estimate indicates that the positive space charge of the fair-weather field near the surface will supply a specific positive charge concentration (q) of approximately 2×10^{-6} coulombs per meter length of the cloud. The equilibrium electric potential of the inner cylinder which results from this

central charge can be approximated by (Wilson, 1958)

$$V_a = \frac{q}{2\pi \epsilon_o \epsilon} \ln \left(\frac{b}{a}\right) \quad \text{(volts)} \qquad (6)$$

which yields approximately 3×10^3 volts.

The boundary of the storm cloud will acquire a neutralizing negative charge resulting from a downflow of negatively charged particles from the highly conducting dynamo region above the storm. This electric current, which is directed upward, must have a magnitude of 10^{-4} amperes to match the upwelling positive current in the cloud. This vertical current has important implications for the electrical structure of the lower atmosphere and the earth's surface. Our electrostatic structural assumptions of the fair-weather situation are immediately invalidated as this upward current punctures the earth-troposphere capacitor, and the following two major conditions will prevail:

a. There will be a $V = IR$ voltage drop along the current path from the storm cloud to the dynamo circuit above. Nominal values of $I = 10^{-10}$ amperes m^{-2} and $R = 10^{15}$ ohm m^2 give potential drops of 10^5 volts, with the top of the storm at the higher potential.

b. The top and sides of the cloud will assume the potential of the dynamo current above the storm plus the difference of (a). This latter item is of major importance, since it has been shown (Webb, 1968b) that the potential drops of the dynamo currents introduce gross horizontal potential variations of the order of 10^6 volts into the global electrical structure of the lower ionosphere. Thus, the storm cloud upwelling of positive charge from the fair-weather field discussed above will have the net result of adjusting the potential of the outer margins of a convective cloud down to altitudes of 1-2 km toward the gross potential of the dynamo region above the storm.

Stergis, Rein and Kangas (1957) have measured the potential gradient and conductivity near 20 km above thunderstorms from the direct current point of view, obtaining results indicating an upward current of the order of one ampere over each storm with maximum negative potential gradients of a few hundreds of volts per meter. Using 200 volts m^{-1} at 20 km, 50 volts m^{-1} at 25 km and the resistivity curve of Fig. 3, the potential drop in this current path approximates 5×10^5 volts under steady-state conditions.

When the dynamo potential above a convective cloud is negative relative to noontime (late afternoon and nighttime; Webb, 1968b), a positive surface charge will be impressed on the earth's surface in the vicinity of the convective cloud, the tropospheric electric field will reverse sign relative to the general fair-weather situation and the potential

difference between the earth's surface and the outer margins of the cloud will be double that of the dynamo circuit to which the storm is connected. Introduction of negative dynamo entials of the order of 6 x 10^5 volts or greater to near the earth's e will induce coronal discharge of positive charge (Chalmers, 196, apter 9). With development of convective systems, enhancements of such space charge by more than three orders of magnitude above the fair-weather values have been observed (Vonnegut, Moore and Botka, 1959). Thus, the 10^{-4} amperes vertical current mentioned above as produced by the fair-weather space charge will be increased to more than 10^{-1} amperes, and the captive charge of the cloud condenser will be increased to more than 10^{-3} coulombs per meter for a total cloud charge of the order of 10-100 coulombs. These values imply general potentials across the cloud condenser system of 10^6 to 10^7 volts, and it is likely that inhomogeneities in the entire process can easily produce the local potentials of 10^8 volts and greater which appear to be required to initiate observed lightning discharges.

The tropospheric return current through thunderstorms must then consist of three modes. The first is upward transport of positive charge in the convective current, and the transport of these charges may represent an added source of energy for the tropospheric electrical circuit. The second is a conduction flow upward outside the convective system involving positive coronal charges migrating upward from the surface and combining with downward-moving negative charges, moving in the forced diffusion mode at higher altitudes and in convective downward motions around the cloud system at low altitudes. The third mode is high intensity upward current flow across the lower atmosphere in intermittent low resistance lightning discharge paths. Convective cells thus establish local electrical structures in which the approaching negative charges from above polarize the earth's surface, producing a negative potential gradient and an upward current flow.

The concept of thunderstorm electrification presented above is parallel to the concepts developed by Grenet, Vonnegut and Moore (Grenet, 1947, 1959; Vonnegut, 1955; Vonnegut et al., 1959; Moore et al., 1962; Vonnegut et al., 1961; Moore et al., 1960; Vonnegut and Moore, 1960; Moore et al., 1958), with the major exception of addition of the horizontally stratified 100 km region dynamo circuit potential to induce corona and activate the electrical processes of convective cloud systems. Convective energy is necessary in initiating this series of events, but the impact of the dynamo electric potentials is overwhelming. These considerations indicate that the partial agreements which have been obtained by numerous thunderstorm electrification theories (Chalmers, 1967) are simply fortuitous, with the basic tropospheric charge-separating mechanism centering on vertical eddy transport of captive space charge.

The tropospheric electrical circuit elements discussed above require that a portion of the circuit lie in the earth. The diffuse global fair-weather current must converge to a few local storm areas for the return trip through lightning discharges. Elementary physical considerations

indicate that these telluric currents will flow in the surface layers of the earth. Since thunderstorms and their associated lightning events exhibit maximum occurrence at low latitudes in the afternoon and evening, these telluric currents must be generally directed equatorward during the daytime and poleward at night.

Electric currents have been known to exist in the earth's surface since the mid-19th Century. Use of long copper telegraph lines over land regions (a 10^7 - 10^9 ohm meter reduction in resistivity) indicated the presence of low-latitude potential differences as high as 10^{-5} v m^{-1} over the surface of the earth with their associated currents. Chapman and Bartels (1962) have summarized the early studies of this phenomenon. They indicate resistivities of a few tenths of an ohm meter in sea water and 1-50 ohm meters in moist loam, with an average value of 100 ohm meters for the general topsoil. Increased resistivity with depth in the ocean results from the colder waters of ocean depths. All considerations indicate that telluric currents are a shallow surface phenomenon.

If a 1 km layer is considered representative, the 10^{-7} - 10^{-8} amperes m^{-2} which Chapman and Bartels reported for continental areas yield integrated half-day hemispheric telluric currents in the 10^2 - 10^3 amperes range. This value is low since high-conductivity ocean paths will provide partial shorts for the continental currents. The intensity of telluric currents may thus be considered adequate to supply the consolidated flow from the global fair-weather charge accumulation to the bases of lightning paths. Redding (1967) has pictorially described the diurnal structure of low-latitude telluric currents, showing that they do indeed flow toward low latitudes during the day and toward the poles at night, indicating that they flow toward the region of principal thunderstorm activity.

Severe complications in telluric current observations caused by technique difficulties, local impedance variations and surface charges prevent detailed association of this current segment with the vertical components of the tropospheric electric circuit. Much more information is also required relative to the location of lightning return paths before an adequate understanding can be obtained. It is concluded, however, that telluric currents are indeed adequate to provide the earth circuit segment for the tropospheric current path of the dynamo circuits.

A detailed schematic diagram of the tropospheric electrical circuitry in a vertical low-latitude zonal plane from the high dynamo potential point at 2 P.M. into the low potential region of nighttime is presented in Fig. 6. The principal driving force (with potential differences of the order of 10^6 v) is located at the base of the horizontally stratified dynamo circuit near 80 km altitude (Webb, 1968b). This force causes current to flow from low to high potential and results in accumulation of a diffuse positive space charge in the region marked A($q \sim 10$ em^{-3}). The principal leakage return path for this potential difference is the dynamo current (approximately 10^5 amperes) circuit through high latitudes at the 100 km level, but a secondary tropospheric return current (I, approximately 1500 amperes) circuit is established in the tropospheric mode illustrated in Fig. 6.

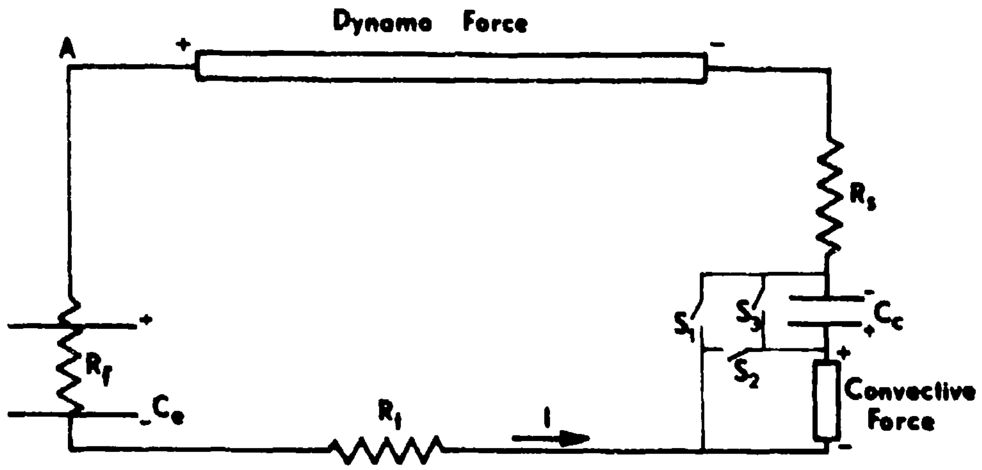

Figure 6. Schematic Circuit of Tropospheric Electrification in a Vertical Low-Latitude Longitudinal Plane from 2 P.M. to after Sunset.

The fair-weather vertical portion of the tropospheric circuit is represented by the resistance R_f and the capacitance C_e. Nominal values of electrical circuit elements in this region are path resistances of 10^{17} ohm m^2, specific capacitance of 10^{-15} farads m^{-2}, current densities of 2×10^{-12} amperes m^{-2} and 3×10^5 volts overall potential difference (lower at the ground) as was discussed above. Telluric impedances (R_t) yield potential drops of 10^{-6} volts m^{-1} with continental current densities of 10^{-7} amperes m^{-2} in the general case. Stratospheric impedance (R_s) above convective storms appears to be equivalent to that of the stratosphere in other locations (Fig. 3), but the area above a convective storm is the site of larger current densities and thus of larger electric fields.

While the conductivity in a cloud is subject to debate, it will be assumed here that in strong convection, high cloud droplet concentrations ($> 10^9$ m^{-3}) will prohibit effective molecular diffusion of charges so that resistance to electrical current flow in the cloud will become very great, with general cloud characteristics of a condenser (C_c, Fig. 6) of 10^{-5}f capacitance for a 20 km length cloud. During initial stages of convective development, the electrical force provided by convective eddy motions will be limited to supplying current flows of the order of 10^{-4} amperes in individual systems. When the convective cloud system becomes effectively connected to the dynamo electrical potential above it, however, coronal discharges from the earth's surface into the low-level air which serves as the source for convective mass transport will strongly enhance the electrical transport process. In this case, the convective transport current will become very strong, possibly contributing significantly to the total current flow of the tropospheric electrical system.

On occasion lightning discharges (S_2 in Fig. 6) may serve to negate this contribution.

Observations indicate that lightning discharges may act as switches (S_1 and S_3 in Fig. 6) to short the charges which accumulate in the cloud-generated open circuit. During the period in which a lightning path exists, the path resistance of the convective segment of the tropospheric portion is reduced many orders of magnitude, and the upward tropospheric current flow will then be through the resistance R_s. When lightning paths exist, the tropospheric leakage current path of the dynamo circuit is

$$R = R_f + R_t + R_s$$

which reduces to $R_f + R_s$ to a good approximation. These are known to be approximately 10^{18} and 10^{16} ohm m^2, respectively (Fig. 3).

Current densities through these two portions of the tropospheric circuit will be different, however, due to the significant difference in cross-sectional areas of these circuit elements. Peak current densities over severe storms appear to be of the order of 10^2 times the fair-weather values, but reasonable mean values over storm areas would be of the order of ten times greater. This would indicate that the potential drop of the fair-weather leg (R_f) is several times that of the strato-spheric branch (R_s). Flow through this voltage divider thus maintains the earth near the average negative potential of the portion of the dynamo circuit under which the convective storms operate.

Since the fair-weather current flow is generally toward the earth even relatively close to thunderstorms, it is clear that the intermittent nature of lightning is of considerable importance. Through this mechanism, the earth is closely related to the mean electrical potential field of the dynamo region above active storms, but the brevity of the events (milliseconds) does not allow the sluggish troposphere (tens of minutes) to approach equilibrium with the new circuit parameters during this special event. The average potential of the earth is thus maintained at a negative value relative to the tropospheric condenser plate by the local dynamic characteristics of this tropospheric circuit.

5. Exospheric Electrical Structure

The vertical distribution of the dynamo currents at low latitudes has been derived by Webb (1968b) from stratospheric tidal circulation data. Chapman and Bartels (1962) and recently Matsushita and Maeda (1965) and Matsushita (1965) have used data on variations in the geomagnetic field to derive the lateral distribution of electric current systems which flow in the upper atmosphere. Under the assumption that these "dynamo" currents are confined to the 100 km region globally by the unique "Hall" and "Pedersen" conductivity profiles it is possible to derive the global current density of that level. Conductivity structures of the 100 km surface may be approximated from published mean electron density data

(Wright, 1962) and magnetic field aspect data (Vestine, et al., 1947) for particular values of collision frequency. Through use of these sources of information it is possible to calculate the electric potential field of the 100 km surface.

The result of such model calculations for Northern Hemisphere fall equinox time is illustrated by the model potential distribution presented in Fig. 7. A high-potential region of the order of 10^6 volts is indicated

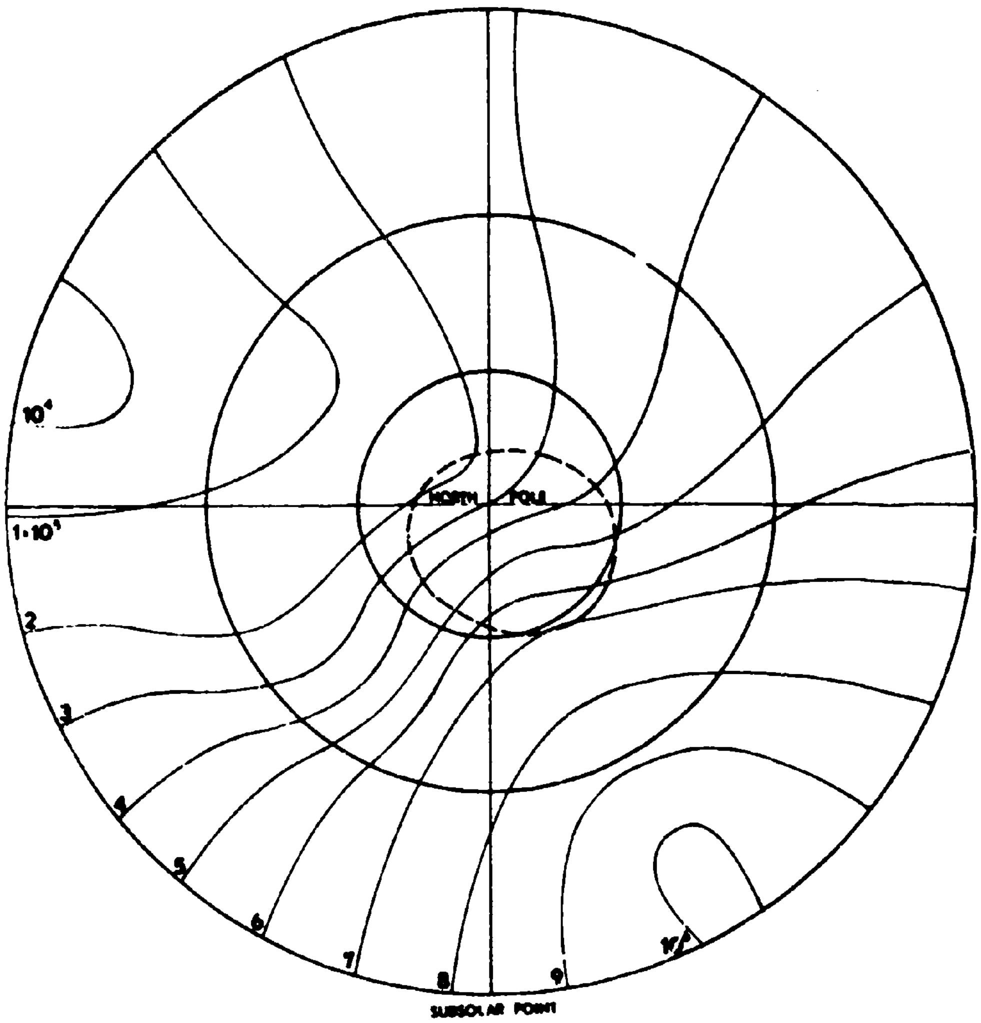

Figure 7. Model electrical potential field for the lower ionosphere at equinox time. Units are volts. The dashed curve represents the auroral oval.

by these considerations to be located in early afternoon low latitudes, with an expansive region of low potential covering nighttime regions. High-latitude auroral regions are indicated to be at intermediate potentials, with considerable variations in potential around the auroral oval. The position of the southern magnetic pole and its auroral oval at the time of Fig. 7 indicates that there will be significant differences in potential of the dynamo regions between conjugate points, even in this relatively symmetric equinox situation.

Consideration of the variations which will be introduced into these hemispheric potential distributions diurnally as a result of rotational and magnetic axes asymmetries indicates that local potentials and conjugate potential differences will vary markedly in the course of a day. In addition, the known gross inhomogeneity of the ionosphere in small scales and the detail structure of the stratospheric tidal circulation and tropospheric lightning perturbations will assure inhomogeneous dynamo currents and thus highly inhomogeneous potential fields. Marked differences will occur at similar geomagnetic latitudes between summer and winter hemispheres as a result of differences in conductivity structure and intensity of the tidal circulations. These differences are in addition to the above-mentioned local and hemispheric variations, with the result that the global potential field of the 100 km level will be very complex indeed. The smoothed curves of Fig. 7 must be interpreted as averaged conditions with gross variations superimposed locally.

All of the above calculations have been based on the assumption that the dynamo circuits are independent current systems which are isolated from other sources or sinks of electrical energy. This is an approximation which, on the lower tropospheric side, has been evaluated (Webb, 1968b) to involve neglect of currents of the order of one percent of the dynamo current system, and thus generally negligible relative to the 100 km dynamo current, and potential structure. An exception is to be noted in the case of short period changes resulting from events such as lightning discharges, where large charge transports (30 coulombs moved 10 km vertically) do introduce gross potential changes for short periods.

Boundary conditions on the upper side of the dynamo currents are less likely to be negligible, however, as a result of currents which may flow in the high conductivity plasma in which are embedded magnetic field lines of the magnetosphere. At some level in the upper ionosphere the known reduction of plasma density and the increase in dynamic impedance (Swift, 1965) with height will reduce the conductivity (increase the resistivity) to the point that substantial electric fields will exist along the magnetic field. These magnetic-field-aligned electric fields will result in acceleration of charged particles to higher energies than are representative of ambient neutral particles and will accelerate the positive and negative particles differently according to mass. In the upper portions of this accelerating region, some of the more favored particles will gain escape velocities and will move out along the magnetic field toward the conjugate point of the other hemisphere where they will execute a reversed but similar program of energy exchange with that upper ionosphere region.

The above described vertical motions will represent new sources and sinks of electric current for the dynamo currents which we have described above and thus modify the potential field of the dynamo region. Under quiescent conditions, these exospheric currents are indicated to be of the order of 10^{-12} am^{-2} (O'Brien, 1964) and thus are reasonably negligible, but there is observational evidence that on occasions of solar disturbances these interhemispheric currents exhibit extreme values of 10^{-5} am^{-2} (Sharp, et al., 1967), and thus may be competitive locally with the dynamo currents in intensity and may introduce gross modifications to the simple E-region potential distribution picture presented in Fig. 7. This is especially to be expected in high latitudes where interaction between the earth and the solar wind can be expected to support large vertical currents.

The dynamo currents of the E-region will be modified by currents flowing through the exosphere in paths formed by the earth's magnetic field and the exospheric plasma. The conductivities of these paths are complex, with charged particle diffusion modes the rule in low altitudes and particle transient modes dominate in the magnetosphere. Buneman (1959) indicates that the magnetospheric longitudinal (along the field) conductivity is given by

$$\sigma_0 = 5.556 \times 10^{-8}\ \omega_{pe} \tag{7}$$

where ω_{pe} is the plasma frequency of the electrons. This indicates a conductivity of approximately .5 mho m^{-1} in the 500-600 region, decreasing to approximately 10^{-2} at high altitudes.

These values indicate that exospheric path resistances on low L shells (L1) are of the order of 10^9 ohm m^2, on auroral L shells (L5) of the order of 10^{10} ohm m^2 and in the polar regions of the order of 10^{11} ohm m^2. These path resistances may be compared with estimated 10^{10} ohm m^2 (Webb, 1968b) resistance of the dynamo 100 km level return current circuit through the auroral zones and the 10^{17} ohm m^2 (Webb, 1968b) resistance of the tropospheric circuit.

In low latitudes, magnetospheric currents will flow as a result of differences in the conjugate potentials of the powered (zonal) and relaxational (meridional) segments of the dynamo circuits. These currents (I_1, Fig. 8) are in the region of the inner Van Allen belt and are thus assumed to be associated with development of that trapped radiation. These currents act to smooth differences between the hemispheric dynamo current generators.

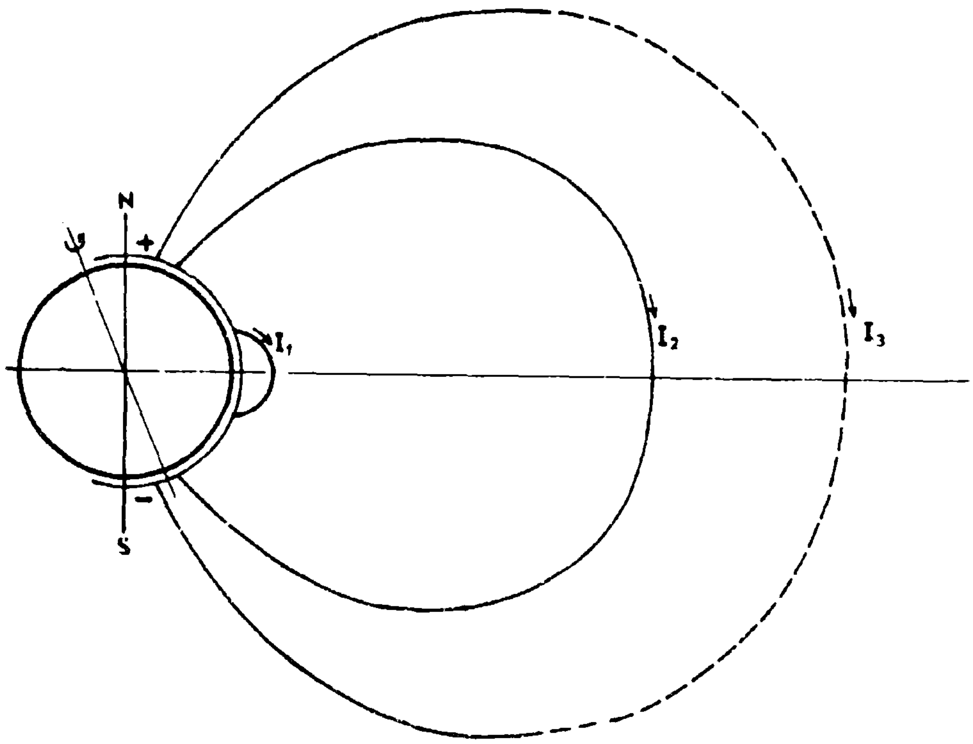

Figure 8. Schematic of exospheric current systems for the case in which the dynamo current potential fields hold the northern magnetic high latitude at a positive potential relative to the Southern Hemisphere.

Zonal flow of the dynamo currents in auroral zone E-regions will result in strong zonal potential gradients around the auroral oval. Inspection of the geometry of the high latitude case (Webb, 1968b) indicates that when the hemispheric dynamo potentials in the driving regions are equal, differing hemispheric meridional path lengths of the dynamo return currents would tend to produce occasional conjugate potential differences of more than 10% of the total dynamos potential gradients, or of the order of 10^5 volts in high latitudes. Exospheric currents along the magnetic field will develop in response to these gradients and tend to reduce them. The result will be current flows (I_2) as is illustrated in Fig. 8.

At high geomagnetic latitudes, the magnetic field lines between hemispheres become electrically completed as a result of interaction with the plasma and magnetic field of the solar wind. Nonlinear acceleration processes will result in potential differences along magnetic field lines, and the interhemispheric potential differences will be reduced with increasing latitudes in polar regions as a result of these current flows. The current

flow in this third magnetospheric current region is designated I_3 in Fig. 8, the dashed portion indicating the uncertain current path through the magnetospheric tail and the solar wind.

These three current systems are assumed to provide support for the ring current which has been hypothesized to circle the earth (Chapman and Bartels, 1962), produced by transverse drift motions imparted to charged particles participating in these magnetospheric currents as a result of accelerating electric fields. The gross geometry of I_3 indicates that it will be ineffective in producing the magnetic effects of the ring current which are observed at the earth's surface. Satellite observations indicate that I_1 is relatively stable. It is concluded, then, that the principal contributor to surface-observed ring current magnetic field changes is probably I_2, presumably as a result of solar wind currents from I_3 through the high-latitude ionosphere and through the I_2 circuit. The currents through I_3 and I_2 are thus directly modulated by the intensity of the solar wind. This is the "indented current ring" of Akasofu and Chapman (1964). Thus, auroral activity, the ring current and its associated magnetic effects, polar storms and other physical processes associated with I_2 and I_3 will vary with these two controlling processes.

Small-scale variations in the dynamo currents will induce inhomogeneities in the interhemispheric current flows, resulting in strong gradients in these currents with magnetic latitude and longitude. These inhomogeneities in ionospheric potentials will introduce variations in exospheric current densities which can be expected to result in electric fields transverse to the geomagnetic field which will, in turn, result in particle motions normal to the plane of these two vectors. Transport of plasma into and/or out of the plasmasphere may be expected to result.

Measurements of precipitation currents in the ionosphere indicate general values of approximately 10^{-12} am^{-2} and maximum values as high as 10^{-11} am^{-2} in middle latitudes (Paulikas, et al., 1966; Mozer and Bruston, 1966), 10^{-7} am^{-2} in auroral zones (O'Brien, 1964; Sharp, et al., 1967), and 10^{-12} am^{-2} in polar regions (Reid, 1965). Observations of the polar electrojet magnetic effects indicate high-latitude ionospheric currents in the 100 km altitude region during disturbed periods of the order of 10^5 amperes which are thus of the same order as the basic dynamic currents. This "ring current", mentioned above, which is indicated by global magnetic field variations under disturbed conditions, is estimated to be of the order of 10^6 amperes if it is located in the L5 regions. Assuming that these currents are segments of the same current system (i.e., the ring current and the auroral electrojet are not completely closed at their respective levels), vertical currents into and out of the ionosphere are inferred. Maximum values of cross-sectional areas of the two available vertical current paths in each hemisphere are of the order of 10^{13} m^2 which then infers magnetic-field-oriented vertical currents greater than 10^{-8} amperes m^{-2}.

Preliminary inspection of the geometry of this situation indicates that optimum conditions for flow of high-latitude exospheric currents will occur at equinox time (Webb, 1968b). This results from the enhanced polar conductivity of the ionosphere which is denied one or the other polar region at solstice time. That is, the circuit of I_2 is characterized by increased path resistance at solstice time.

6. Conclusions

The considerations presented above provide a coherent global system of electrical currents in the earth's environment. The principal driving force is indicated to be vertical transport of positive ions in the lower ionospheric region. Through the Hall effect, the dynamo currents are powered, and tropospheric and exospheric currents simply represent leakage paths for the basic dynamo currents.

The model of earth electrification presented here is at strong variance with previous concepts of electrical phenomena in the earth's vicinity. In particular, introduction of neutral-electrical interaction as the basic motivating force of the general electrical structure represents a distinct new line of reasoning. Long-held views of thunderstorm processes as the basic energy source for the lower atmosphere and more recent models of magnetospheric processes as the basic energy source of the upper atmosphere lose some of their flavor in light of these new considerations. The idea of an equipotential ionosphere appears at this time to be clearly in error.

The simplest physical considerations would indicate that a unified global electrical structure would be the most likely case. Maintenance of isolated independent electrical systems in various parts of the atmosphere would appear to be a very difficult situation to achieve. Failure of the various segregated models to effect adequate explanations for the observed local electrical structure and particularly for the interface structure which must exist has provided some indication of their inadequacy. Experimental difficulties have in many cases precluded confirmation of postulated structure and today remain the most difficult obstacle to further progress.

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13. ABSTRACT

The atmospheric electrical structure of the earth is postulated to be controlled by a motivating force in the lower ionosphere which is produced by interaction between neutral atmosphere tidal circulations and the ionospheric plasma in the presence of the earth's magnetic field. Associated electric fields power the dynamo currents through the Hall effect with a resulting development of a gross electric potential distribution in the lower ionosphere. Asymmetries in these hemispheric potential distributions result in exospheric current flows in low L-shells, and larger differences in potential produced by dynamo return current flows in high magnetic latitudes result in strong currents through high L-shells between auroral zones. Vertical thunderstorm currents with their associated lightning discharges effectively connect the earth to a low potential region of the dynamo circuit and thus supply the earth with an average negative charge which motivates a leakage tropospheric electrical circuit. In addition, the dynamo currents maintain the magnetic polar regions at different potentials with a resulting electrical exchange with the solar wind through the earth's near space. These considerations indicate that observed electrical and variable magnetic phenomena near the [illegible] all part of a single comprehensive electrical current syst[illegible]

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